A Field Guide : The Kelleys Island Glacial Grooves, Subglacial Erosion Features on the Marblehead Peninsula, Carbonate Petrology, and Associated Paleontology[1]

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ABSTRACT. **This field trip provides an opportunity to reevaluate the processes responsible for some subglacial bedrock erosion features in northern Ohio. Beginning in the 1830s, quarrying operations on Kelleys Island, OH, have uncovered several giant grooves on the bedrock surface. One such groove remains for investigation today. There is agreement that these features were formed mainly in a subglacial environment, but specific agents and mechanisms remain matters of controversy. The dominant second-order features within the giant groove are cigar-headed ridges with furrows present on sides, at heads, and commonly well in front of heads. Fractal analysis of high-resolution transverse profiles highlights the geometric differences between small-scale features (striations) and large-scale erosion forms, with the break in roughness occurring at a scale of 10 cm (4 in). The genesis of the large-scale features warrants further analysis and discussion. Elsewhere on the island, wave-cut notches and chutes along joints can be observed as results of Holocene shoreline erosion. A large glacially-planed surface on the nearby Marblehead Peninsula displays a range of erosional forms more typical of the region. These forms are developed in the same formation exposed in the Kelleys Island giant groove, the Devonian Columbus Limestone, consisting of highly fossiliferous, subtidal marine carbonates. The glacially smoothed surfaces at Marblehead and in the Kelleys Island groove provide many opportunities to examine fossil communities in planar section, and to evaluate the influences of the variable petrology and individual fossils on bedrock erosion by subglacial processes.**

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INTRODUCTION

This field trip is an opportunity to examine and discuss the origin of an unusual set of geologic features: a giant glacial groove at Kelleys Island, the smaller erosional features within it, and additional subglacial erosion features on the nearby Marblehead Peninsula. On Kelleys Island, giant grooves (or megagrooves), several meters deep and wide, were uncovered during quarrying operations and were subsequently destroyed by quarrying (Ver Steeg and Yunck 1935), the sole exception being the site we will visit at the Glacial Grooves State Memorial. Photographs of the other examples, taken over the last century, remain as evidence of their characteristics, and a number of these photos have been published (Carney 1908, Ver Steeg and Yunck 1935, Goldthwait 1979, Hansen 1988). Although there is general agreement that the megagrooves and the smaller erosional features contained in them were formed in a subglacial environment, there is little further agreement among researchers on the specific agents and processes of erosion. This controversy began more than a century ago, and remains active today.

At the Glacial Grooves State Memorial site, it is useful to explore various qualitative and quantitative ways of describing the features seen, and then to attempt as a group to evaluate the various hypotheses of formation by ice tooling, meltwater erosion, multiple-stage development, and other means. In keeping with this approach, this field guide includes lists of pertinent questions that visitors to the site might consider.

Bedrock character may have a large or small role controlling the geometries of the large-scale and small-scale erosional features. Thus, study of the Devonian Columbus Limestone is necessary. It is helpful to first become acquainted with this bedrock on a less complex, glacially-planed surface at another old quarry site on the nearby Marblehead Peninsula. The sedimentology and paleontology of these rocks are worth consideration as examples from a subtidal marine carbonate depositional environment, as well as for their potential influence on variable mechanical and chemical resistance to erosion. The glacially-smoothed surfaces at both sites provide excellent opportunities for viewing fossil communities in section.

A visit to the Marblehead site also allows one to place the megagrooves in regional context. Carney (1910) notes that during stripping for quarry operations on Kelleys Island, large flat areas without the imprint of glacial erosion were uncovered. These surfaces, now quarried away, were marked by sudden transitions to planar eroded surfaces, which contained the incised grooves. Ver Steeg and Yunck (1935) note that large flat areas border the island, some striated, and along the east shore exhibiting numerous chatter marks. They also note a seeming concentration of the giant grooves on the higher parts of the island. While no large, glacially-planed surface remains at the Glacial Grooves State Memorial, such a surface is present for examination at the Marblehead site.

While on Kelleys Island, one can visit a site of modern active erosion of the Columbus Limestone by shoreline processes, on the west side of the island's northeastern point. At Table Rock, wave-cut notches and preferential erosion along joints are both in evidence.

Bedrock Stratigraphy

The Columbus Limestone is one of several Middle Devonian carbonates deposited on the southeastern flank of the Findlay Arch. It conformably overlies the Lucas

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Formation and underlies the Delaware Formation. It is subdivided by Swartz (1907) into the Bellepoint Member, Marblehead Member, and the Venice Member on the basis of fossil content and lithology. The Columbus Limestone is regionally correlative with the Onondaga Formation of New York, the Jeffersonville Limestone of Indiana, and the Detroit River Group of Michigan (Sparling 1985, Oliver 1976). The regional dip is approximately 4 m per km (20 ft/mi) to the southeast, with local variations.

The Columbus Limestone is a highly fossiliferous, thin-to-thick-bedded, tan carbonate consisting of dolomudstones, dolowackestones, dolomitic packstones, and grainstones. The percentages of bioclasts and sparry cement increase upward in the section, and the dolomite content and porosity decrease upward. Faunal diversity also increases upward in the section. The overall vertical changes in facies within the Columbus Limestone and the underlying Lucas Formation describe a marine transgression. The depositional environments revealed by the Columbus facies are all subtidal marine, but they change upward from semi-restricted to normal marine.

Glacial History

Glaciers flowed through the Lake Erie basin in several different directions. Ver Steeg and Yunck (1935) report four distinct movements of ice across the western end of the basin. The first was to the southwest, but yielded to a southern flow during full glacial conditions. During recession, the pattern returned to a southwest-west direction, the dominant pattern revealed by the eroded forms today. A last "feeble" north to south flow is also reported. Goldthwait (1979), on the basis of till weathering and limiting radiocarbon ages, shows that these occurred during the late Wisconsinan glaciation. Thus, the dominant flow occurred after 24 and before 15.5 ka (post-Hiram till). Goldthwait (1979) argues that most of the erosion probably occurred as the ice sheet warmed during deglaciation. The features to be seen on this trip probably formed rapidly.

Recent History

Ver Steeg and Yunck (1935) provide much information on the postglacial history of Kelleys Island, which is only summarized here. There is archaeological evidence for Indian occupation from approximately 14,000 years ago, and the last Indians left the island soon after the War of 1812. Quarrying of limestone began in the 1830s, near the location of the present Glacial Grooves Memorial, and was a mainstay of the island economy for more than a century. Crushed rock from the upper Columbus Limestone was in such demand for lime, flux, and road stone by 1935 that Ver Steeg and Yunck comment (p. 430) that, "...the whole top of the island is being removed from west to east; the average depth of the vast quarry is 25 feet."

Around the turn of the century, the island population exceeded 1,000, but the present year-round population is about one-tenth that number. The shallow, limy soils and moderate lake climate supported a large grape and wine industry on the island in the late 1800s and early 1900s (Ver Steeg and Yunck 1935). Annual mean lake levels have fluctuated within a 1.6 m (5 ft) range in the period from 1860 to the present, with record high levels reached in 1986. Superimposed on these long-term trends are seasonal fluctuations of about 45 cm (1.5 ft), and surge effects during severe storms that can be more than 2.5 m (8 ft) above or below normal lake level (Quinn 1988).

SUBGLACIAL PROCESSES RESPONSIBLE FOR EROSIONAL FORMS

Three glacial mechanisms remove bedrock: abrasion, plucking (quarrying), and subglacial erosion by meltwater. Abrasion is the mechanical wear resulting from rock fragments embedded in glacial ice moving across the bedrock. The tools gouge or scrape the bedrock on a small scale. Plucking (quarrying) involves large-scale bedrock failure (fracture), with separation and glacial entrainment of rock fragments. Subglacial meltwater can remove bedrock by either chemical dissolution or abrasion. The real task is to determine the relative role, influence, and magnitude of these three processes at any one outcrop.

Let us now briefly consider the various processes of bedrock removal, their controls, and resulting features. Drewry (1986) suggests that major factors of an abrasion model are:

$$Ab = f\,[dH, F, Up, Co, c, S]$$

where Ab is the abrasion rate, dH is the relative hardness between the cutting tool and the bedrock, F is the downward force pushing on the tool, Up is the speed of the tool, Co is the concentration of the tools, c is the ratio of worn tools removed compared to new tools added, and S relates to the shape of the tool compared to the bedrock. Maximum erosion rates are achieved when the tool is much harder than the substratum, when the force is balanced (too much force can cause the tool to become lodged), when the tool velocity is high, when debris concentrations are near 10 to 30%, when the tools are replaced, when the tool is pointed, and when the bed slopes into the ice surface. Much of this theory stems from the work of Boulton (1974) and Hallet (1981). Hallet demonstrates the interesting result that low debris concentrations are necessary for high abrasion rates. High debris concentrations impede the particle velocities to the point that overall abrasion rates are reduced. An individual striation on the bedrock will have a size, shape, and length that depends on the hardness of the tool.

On a larger scale are the fractures of the rock, induced when large or rigidly held clasts impact the rock. As the ice moves a clast into contact with the bedrock, a stress system is set up and the rock will fail if the induced stress exceeds the strength of the rock. Fractures are most likely when the bedrock slopes into the oncoming ice, providing a higher component of normal stress. The resulting features are known as chattermarks, crescentic gouges, lunate fractures, and crescentic fractures, depending on their shape and orientation relative to ice flow. In places, close examination of large striations may reveal a series of small fractures indicating that the two processes are more closely related than might be expected.

Glacial meltwater is an optimum fluid for abrasive erosion. At near freezing temperatures its viscosity is high;

this allows more sediment to be carried in suspension. The fine-grained material can abrade the bedrock by impact. If larger particles are carried, they will saltate over the surface, causing localized fractures and removal of the bed. Sharpe and Shaw (1989) argue that the action of meltwater can cut many of the larger molded forms common on glaciated surfaces. At high water-flow velocities (more than 12–14 m/s, 39 – 45 ft/s), the vapor pressure of the water is exceeded, forming air bubbles. Collapse of these bubbles within the fluid stream results in strong local pressure gradients, fracturing of rock, and high erosion rates. Thus, we should look for pits to reflect this condition. Chemical erosion has been shown to be locally important, but it is very difficult to assess on surfaces of former glacier cover. In some cases, precipitation reflects a degree of balance between dissolution and deposition in the chemical system.

We offer a ternary diagram (Fig. 1) for visualization of the relationship between these processes. This approach requires one to consider explicitly the relative contributions of pure ice, water, and debris (Fig. 1A). Different combinations of these materials produce various types of erosion (Fig. 1B), identified by various names. In general, *abrasion* is an overworked term applicable to a great variety of processes, and we suggest that more specific terms be used to clarify discussion. Our estimate of the relative effectiveness of each of these materials and processes in the glacier system is also given (Fig. 1C).

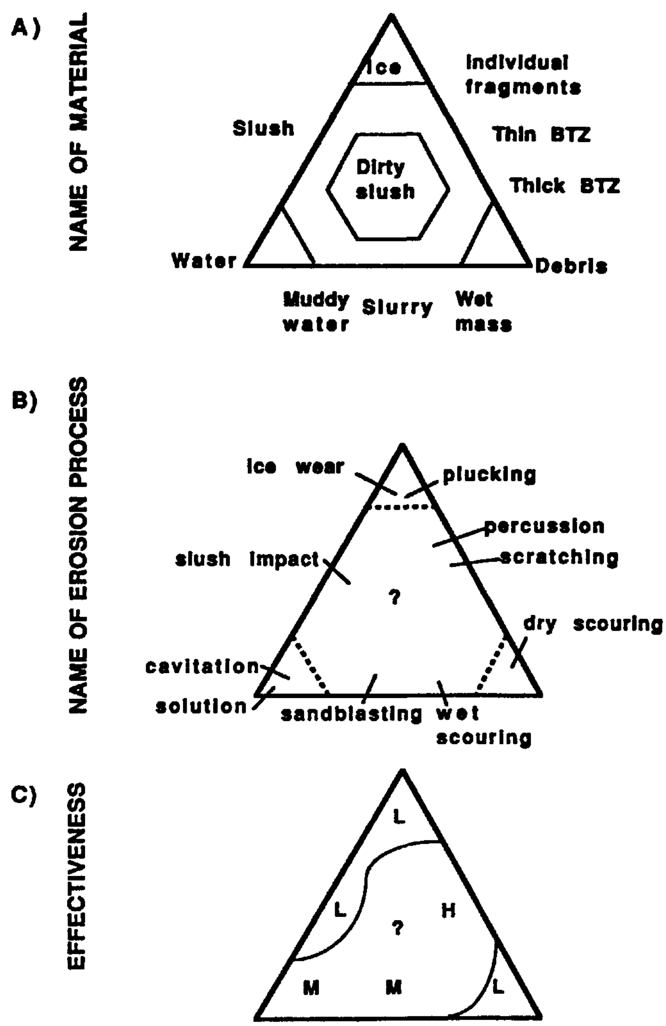

FIGURE 1. Schematic diagram of the materials (A), processes (B), and effectiveness (C) of erosion in the subglacial environment. The acronym BTZ stands for "basal transport zone," or subglacial mat of debris. Estimates of effectiveness are subjective in terms of relative contributions (L = low, M = medium, and H = high). It would appear that any of the processes can be the dominant one depending on the exact conditions present at the glacier bed.

FIELD TRIP STOPS

Stop 1: Glacially Planed Surface, Marblehead Quarry

LOCATION. Note that the Kelleys Island, OH, 1:24000 USGS (U.S. Geological Survey) topographic quadrangle covers all sites visited in this trip, and will be a useful supplementary map for independently run trips. Other field guides to be aware of include ones by Forsyth (1971) and Feldmann and Bjerstedt (1987).

Following State Route 163 eastward along the Lake Erie shoreline, enter the town of Marblehead, continue to the junction with Alexander Pike, and turn south (Fig. 2). On top of a rise 1.4 km (0.9 mi) along the Pike from the intersection, is a gate on the east side of the road. Park here, pass around the gate, and walk eastward on the narrow jeep trail. About 300 m (1,000 ft) from the gate, the first large, cleared, glaciated surface appears. PERMISSION must be obtained to enter this site. Contact the Standard Slag Company, Marblehead Stone Division, 522 Limestone Dr., Marblehead, OH 43440.

GENERAL INTRODUCTION TO THE SITE. This flat glaciated surface exposes approximately 20,000 square meters (200,000 sq ft) of the Columbus Limestone (upper Marblehead Member). At first glance, the surface appears to be one single bedding plane, but variable dip of the section and a small amount of surface relief results in exposure of an oblique section 4 m (13 ft) thick. This section can be seen in its entirety by traversing from the southeast corner of the surface (Point of Interest #2, described below and marked in Fig. 2) to the northeast corner (Point of Interest #4), walking updip and, thus, down-section.

Although many interesting features of glacial erosion can be observed here, the most notable is the overall planar nature of the surface. Although it has more relief than is first evident, it is remarkably flat (slopes of 1%). Most glaciated rock surfaces consist of rounded hills and depressions with relief of about 0.5 m (1–2 ft), and such surfaces are found here, in the woods near Point of Interest #1.

Parallel striations run across this flat surface with orientations near 255°. Individual striations range from 1 mm to more than 5 cm in width and may extend several meters. Fracture marks can be observed at several locations within the larger striations and on bedrock slopes that dip to the east.

POINT OF INTEREST #1. This first large exposure of glaciated surface appears in an elevated clearing between two quarry ponds (Fig. 2). Here, a second set of striations trending 150–155° can be observed, occurring only on the high ridges between the scorings of the 255° set. The second set is more difficult to detect than the first set.

POINT OF INTEREST #2. Located in the southeast corner of this glaciated surface are several exposures of abraded ripples which define the contact between the top of the

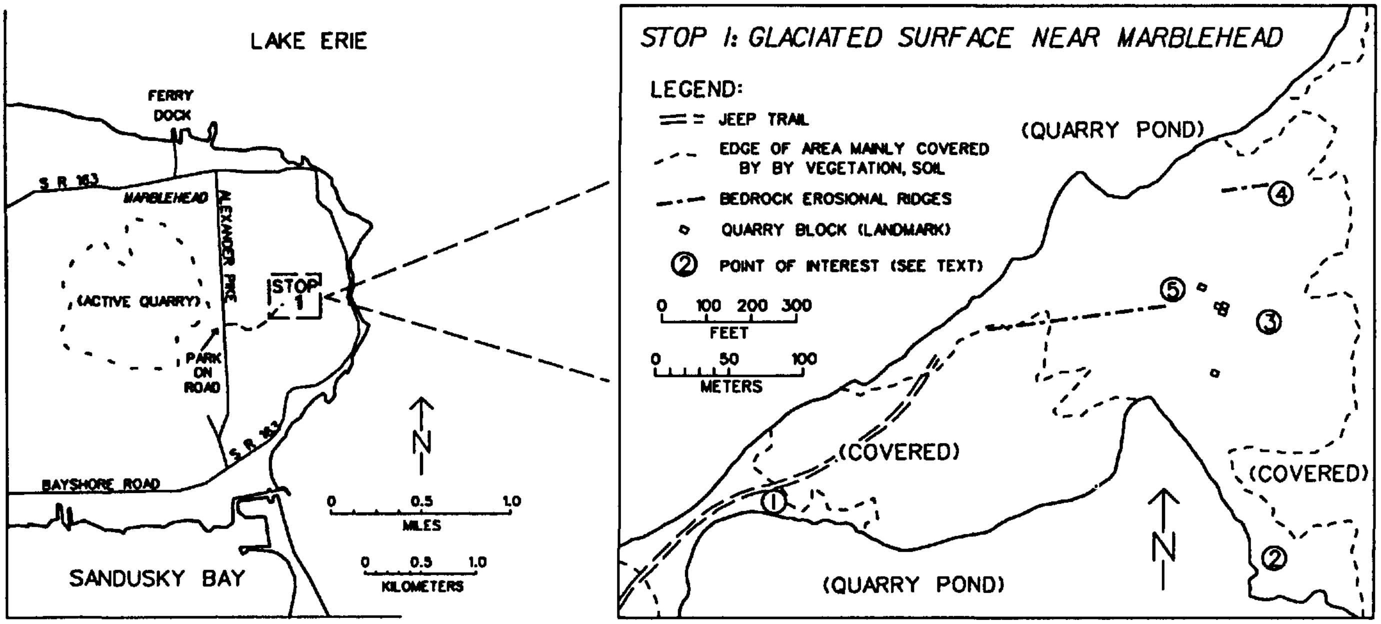

FIGURE 2. Location and site maps for Stop 1, just south of the town of Marblehead (east of Port Clinton and north of Sandusky, on the Marblehead Peninsula, OH).

Marblehead Member and the base of the Venice Member. The undulating surface is completely exposed in one area, through erosion of the overlying rock; just a few meters away the undulations have been truncated by the glacier, exposing both lithofacies. The ripples are symmetrical, with wavelengths averaging 0.5 m (1.5 ft), and trending 335°. According to Bjerstedt and Feldmann (1985) this surface represents a diastem or break in sedimentation and was cemented penecontemporaneously, forming a hardground. Chapel (1975) has described a similar smooth, undulating surface from many other sites throughout central and north-central Ohio, and finds that the position of the rippled bedforms in the section, and even the trend and wavelengths, remains nearly constant.

POINT OF INTEREST #3. Exposures of thousands of solitary rugose corals of the genus *Zaphrentis* occur 100 – 150 m (300 – 450 ft) north of the rippled bed forms. Although they appear in broad zones that widen and narrow in the oblique exposure, they are actually part of continuous horizons, 10 – 20 cm (4 – 8 in) thick, in the vertical section. The lithofacies is a grainstone containing abundant pelmatozoan debris and charophytes (*Moellerina greenei*). Other conspicuous fauna in this facies include the colonial corals *Hexagonaria* and *Favosites*, encrusting stromatoporoids and corals, planispiral gastropods, and strophomenid brachiopods. The environment of deposition was a subtidal shoal with moderate to high wave activity that supported an abundant and diverse fauna (Frank 1981).

Erosional remnants known as crag and tail features (positive ridges extending downcurrent from obstacles), are especially notable in this area. Here, corals form the resistant obstacles that have protected the bedrock lying to the west from erosion. Although the crags stand up to 10 cm above the planar surface, the tails become lower to merge with the surface over a distance of about 5 m. Note that several of the fossils east of the crag and tail features have been completely planed off. Some crags and tails on other parts of the surface have depressions or furrows along their sides, and occasionally in front as well.

POINT OF INTEREST #4. Approximately 100 m (300 ft) north of Point of Interest #3 is the eastern (up-glacier) end of a rock ridge that crests about 30 cm (1 ft) above the surrounding surface. In this area, a dolowackestone lithofacies occurs, consisting of a relatively sparse fauna, but with abundant horizontal and vertical burrows and with Tasmanitids. Clumps of colonial corals, commonly centered around very large individuals of *Eridophyllum*, may have acted as sediment baffles (Bjerstedt and Feldmann 1985). *Favosites, Hexagonaria,* and chonetid and strophomenid brachiopods are also found within these clumps. The presence of Tasmanitids and absence of faunal diversity suggest that this facies was deposited in a semi-restricted subtidal setting (Frank 1981).

The long, remnant ridge marking this point (Fig. 3) is one of two such features to be seen on the surface. This one has furrows (filled with soil) extending east of its "nose," possibly the inspiration for its local name, "The Locomotive." The nose does not display striations, but rather has a fractured surface. Striations cover the main part of the ridge. Note also the slight depression in front of the nose. At its western end, the ridge has curvilinear striations that trace from the north side of the ridge, swing south, and join the striations on the 255° path.

POINT OF INTEREST #5. Proceeding back west along the northern part of the cleared surface toward the dirt road, the route intersects the larger of the ridges, which extends at least 115 m and is up to 3.8 m wide. The furrows do not extend to the east of the nose. However, the nose is highly fractured and has small pits near its base. Note a smaller ridge on the south side of the main ridge at its midpoint. The upper surface of the ridge is at the same elevation as the pitted bedrock surface to the north.

Questions

Several obvious and several subtle questions are worth

FIGURE 3. The head of the smaller erosional ridge, "The Locomotive," on the glacially planed surface near Marblehead, Stop 1. The view is westward, down ice-flow direction. Note the vegetation-filled furrows to either side, and also wrapping partly around the head. Note, also, fracturing on the up-ice end of the crest.

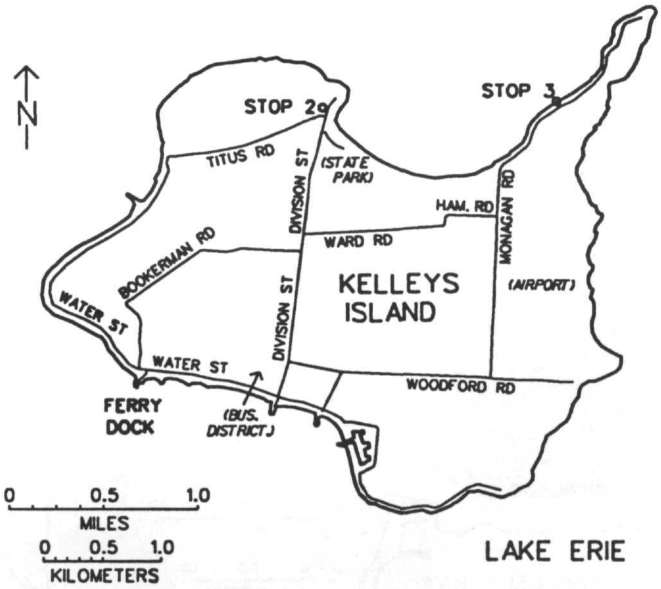

FIGURE 4. Location map for Stops 2 and 3 on Kelleys Island, OH.

considering at this outcrop; these relate to the subglacial erosion features, their areal distribution, the geometric relationships between them, and their origin.

• Why is this extensive surface so flat? The planed nature of the main exposure indicates that a very delicate balance existed between erosion and the resistive forces for some length of time. Why would such a balance occur? What erosion processes are responsible? Is the flat surface simply a result of lithologic control? Does the merging of crag and tail features (Point of Interest #3) with the surface have any significance? What is the magnitude of erosion here?

• Why are there parallel striations down ice from some fossils and not others? Some crag and tail features have rounded cross-profiles whereas some have square heads (rare); furrows may or may not be present. Are all of these features formed in the same way? The large ridges appear to have form characteristics in common with the crag and tail features; do they have the same origin?

• What is the role of individual fossils or fossil assemblages in determining the shapes, sizes, and positions of subglacial erosion features on scales of a few centimeters and of the whole outcrop?

• What is the sequence of relative ice-flow directions? Do the striations trending about 150° represent a flow after the westward flow? In this case, wouldn't they simply be draped over the topography already cut? As an alternative, the 150 – degree set could be older and the westward set younger. The second possibility implies that the westward erosion only cut localized, broad, shallow grooves. Ver Steeg and Yunck (1935) report two ice flows to the southwest; which is the dominant one? The relative age assignment is important to interpretation of the conditions of the various flows.

Stop 2: Glacial Grooves State Memorial, Kelleys Island

LOCATION. Leaving Stop 1, return north on Alexander Pike to State Route 163, turn west, and proceed nearly 0.4 km (slightly more than 0.2 mi) to the sign for the Kelleys Island Ferry in Marblehead, marking a street on which you proceed north to the ferry dock (Fig. 2). Ferry schedules change several times during any year, so it is important for leaders to call the Neuman Boat Line before trips to obtain departure and return schedules appropriate to trip date, as well as rates for large groups and their vehicles. Plan to arrive at the docks with time to spare during busy periods of the day and year. The ferry takes somewhat less than half an hour to cross the 3.5 mi to and from the island.

Leaving the ferry dock on Kelleys Island, turn right (east) onto Water Street and drive into the business district (Fig. 4). At the intersection with Division Street, turn north and drive 2.5 km (1.6 mi) to the Glacial Grooves State Memorial. There is a small parking area at the grooves. Camping is available in the adjacent Kelleys Island State Park.

The megagroove itself is surrounded by a low chain-link fence to keep casual visitors off the grooves. This is to protect the grooves as well as the visitors (there is a sheer drop at the west end). OBTAIN PERMISSION to enter the fenced area beforehand by calling the Lake Erie Islands State Parks Office in Port Clinton. Of course, no rock hammers should leave vehicles at this site. Once inside the fence, please do not step on the loose rocks lying on groove surfaces; this will make new striations and ruin the outcrop for others. Removing such loose rocks (if not still resting in place) when leaving will help reduce this problem.

GENERAL INTRODUCTION TO SITE. Geologists have visited,

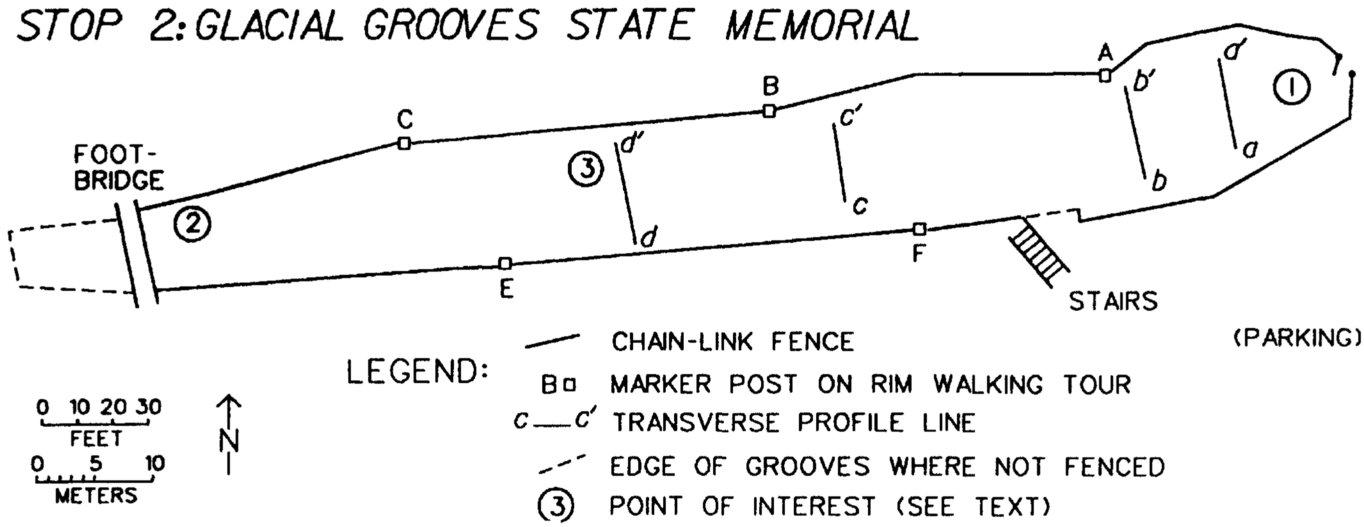

FIGURE 5. Site map for the Glacial Grooves State Memorial, Stop 2. The marked topographic profiles crossing the megagroove are shown in Fig. 9.

studied, debated, and disagreed about the origin of these features since they were first uncovered in the early 1800s. The debate seems to center on the relative role of ice, debris and water (the position on Fig. 1). Some suggest erosion by essentially dry, very debris-rich ice. Carney (1910) suggests that the local bedrock joint patterns could supply localized concentrations of debris that would eventually become detached from the moving ice and focus erosion in the grooves because of the overlying weight of the ice. This further develops some of the views put forth by Chamberlin (1888).

Others suggest erosion by ice carrying no unusual concentrations of debris. Goldthwait (1979) invokes ice converging into existing subaerial stream channels with increased flow rates to erode the grooves. He suggests that meanders and small grooves resulted from vortices or eddies in the ice.

Hypotheses suggesting groove formation by meltwater are of two types. Whillans (1979) argues that channels of subglacial meltwater removed the limestone by chemical dissolution. Abrasion by water-borne particles has been more commonly suggested. Some very early ideas invoked "diluvial boulder action" for the grooves, but workers in the late 1800s argued strongly for a glacial origin because of the striations, and consideration of water associated abrasion was dropped. However, Sharpe and Shaw (1989) make a strong case for meltwater abrasion to cut giant grooves at Cantley, Quebec. Their outcrop is marble with granitic and volcanic inclusions, but it nevertheless possesses many of the erosional forms seen at Kelleys Island: obstacle marks (similar to what are called "cigar-headed ridges" below), channels, sichelwannen, and striations. Their argument for meltwater is based on the comparison of several of these forms to similar forms produced in laboratory erosion experiments (Allen 1982) and seen in fluvial erosion areas.

In summary, the processes suggested to be responsible for the grooves range over most areas of the triangle in Figure 1B. We offer no clear answers, but present some new measurements and build on recent glaciology theory to pose some new questions.

SPECIFIC FEATURES OBSERVED AT THIS SITE. The first sight of the grooves on approach from the parking area (Point of Interest #1, Fig. 5) presents linear erosional features apparent at many scales. Goldthwait (1979) divides the features into four size orders: the single, large groove itself (or megagroove), a set of remarkably deep second-order grooves within the megagroove, striations, and polish. The large groove is one of several that have been uncovered on the island, each being 5 – 20 m wide and 100 to 400 m long, incised two to six meters (7 – 20 ft) into otherwise flat planar bedrock. Observed megagrooves have all sloped downward to the east, and have been fairly linear, with curves up to 20° from the dominant ice-flow direction (250°). Striations trace up to 2 m (7 ft) in the flow direction, and are draped over all other features. Polished rock was observed when the present groove was excavated in the early 1970s, but the polish has since dulled and chipped off (Goldthwait 1979).

The second-order or "sine" grooves (Goldthwait 1979) attract the most attention and debate. Strictly speaking, these are the smaller (10–90 cm wide, 5–50 cm deep, and 5–40 m long) depressions lying on the floor and sides of the megagroove. Between pairs of these lie ridges of about the same dimension. The ridges end in the up-ice direction in rounded ends (cigar ends, or "bulging" [Carney 1908]). The "sine" grooves may extend around the ends, or up-ice beyond them, and have been called scoop marks or furrows (Goldthwait 1979).

A better perspective for discussion might be a unit that is the sum of these second-order features. The cigars have "sine" grooves on their sides and may have several nested furrows well in front (up to 1 m [3 ft]) of the heads (lower left of Fig. 6). A working term, "cigar-headed ridge" (CHR), will be used below to describe this combination of features. The striations on the sides and top of the CHRs are parallel and show little variation. At the heads, however, they show divergence and are not as well developed. The furrows may wrap completely or partially around the heads. In some cases slight depressions, rather than furrows, form in front of the heads; at the junction of those depressions and the heads, we have observed small

FIGURE 6. Westward (down ice flow) view along the megagroove, Stop 2. The cigar-headed ridge in the right foreground shows relatively narrow furrows on either side, and several furrows extending well in front of the head. Scale rod is marked in 10 cm (4 in) increments. A more subtle cigar-headed ridge appears on the left, about 0.5 m (2 ft) from the end of the scale rod. A much larger example of same form is the bulge to Tom Lowell's back. The two smaller ridges are truncated in the down-ice direction by the furrow developed on the right side of the large ridge head.

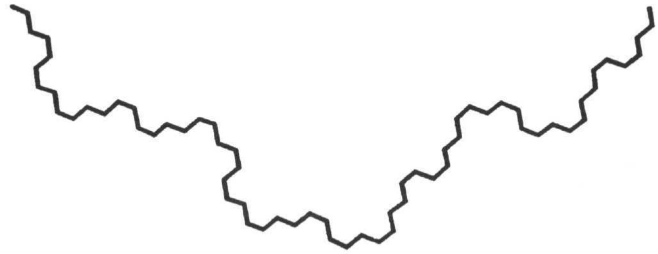

FIGURE 7. A portion of an "alternate Koch curve," a geometric construction that shows the same features on large and small scales ("self-similarity").

FIGURE 8. Modified contour gage for high-resolution topographic profiling. The leveled swing arm records orientation of the 12.5 cm (5 in) profile so that it may be reconnected properly with adjacent traced profiles, in order to represent larger scale forms. The individual steel wires in the gage are about 1 mm in diameter.

pits. At the down-ice ends of the forms, the ridges and furrows are truncated or modified by the appearance of other CHR's or other irregularities. We suggest that most of the forms have this general makeup, and the combination of partially eroded forms and superimposed forms produces most of the curved features observed in the megagroove.

Other features are worth examining. Their different forms may indicate different processes at work, or help to narrow down the range of generally prevailing processes. At some places the lowest portion of the megagroove floor appears to meander. More pronounced cases of such meandering have been observed in megagrooves now destroyed (see Fig. 6 in Goldthwait 1979). Branches of the megagrooves, divergent down-ice, have also been noted at other locations, and there is one example here (Point of Interest #2). Note that the branch channel has a bedrock high located in the middle of it. At the mid-point of the megagroove on the north wall (Point of Interest #3) is a stepped channel that rises 2 m above the floor. Along the northeast side of the groove is a vertical pothole (Goldthwait 1979). Note the similarity to a feature in Quebec (Fig. 8 in Sharpe and Shaw 1989).

FURTHER GEOMETRIC DESCRIPTION. The four size orders of glacial scoring described by Goldthwait (1979) highlight the fact that any high-resolution topographic profile across the megagroove will be a complex geometrical form, with small indentations superimposed on large indentations cut in even larger indentations. However, from the alternative viewpoint of fractal geometry, a shape made up of the same geometrical elements overlaid at many different scales is the most basic of forms. An example of such a "self-similar" shape (Fig. 7) is a portion of an "alternative Koch curve" (Mandelbrot 1983). In the paragraphs to follow, results obtained from high-resolution transverse profiling of the megagroove, and fractal analysis of those profiles, are reported.

Standard surveying methods are not very helpful when one wishes to profile a strongly undulating rock surface over a distance of several meters with resolution near the millimeter scale. The solution applied here was to lay out a transverse profile line with tape and transit, and then transfer the surface profile to paper in 12.5 – cm (5 – in) segments, using carpenters' contour gauges (Fig. 8). Swing arms with bubble levels attached to the gauges allowed them to be pressed against the rock surface from any convenient angle and still be correctly oriented in relation to horizontal lines on the paper. The traced paper records were digitized, allowing whole profiles to be reconstructed as computer data sets.

A viewing of four resulting transverse profiles (Fig. 9) leads to some qualitative observations. The profiles look quite irregular, in the sense that the second-order grooves

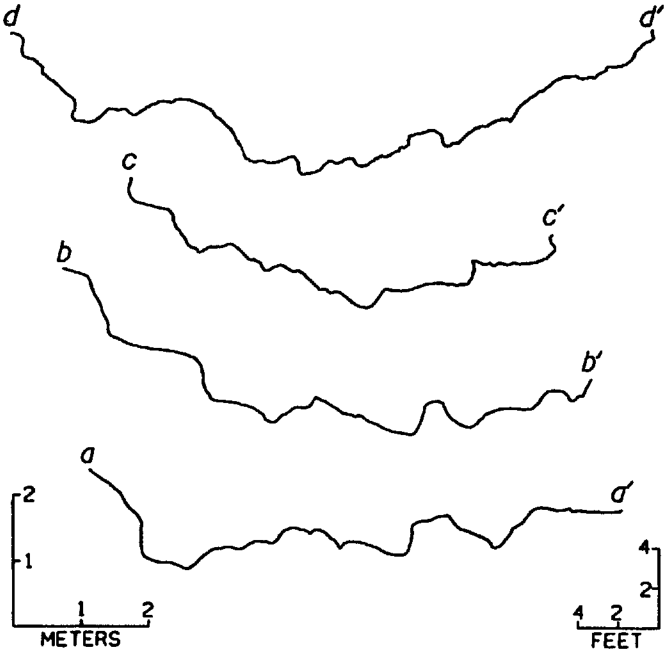

FIGURE 9. Topographic profiles across the megagroove at the Glacial Grooves State Memorial. Sizes and shapes of crests and hollows vary considerably along each profile. Much detail in the profile data sets is not apparent here, but examples of true limits of resolution are shown in Fig. 10.

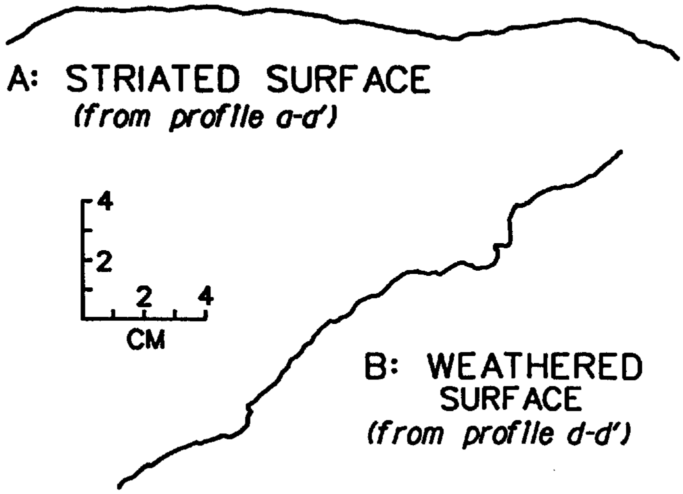

FIGURE 10. Details from transverse profile data sets. The subdued topography of a striated surface (A) is shown by a 10-cm sample from transverse profile *a-a'* (Fig. 9). An example of a weathered surface at the same scale (B) is given by a small portion of profile *d-d'* (Fig. 9).

and associated ridges do not show constancy of shape or scale. The grooves can be broad bottomed or narrow bottomed, and the same can be said for the tops of ridges. In fact, if the larger upward concave form of the megagroove were ignored or removed from each profile, it would be difficult to guess which way was up.

Three of the profiles were collected at places in the megagroove where fairly fresh glaciated surface is preserved. Looking more closely at small sections of these profiles (Fig. 10), the silhouettes of individual striations appear (Fig. 10A). Again, the surface appears irregular in profile; the scratches are different in size and shape. However, the relative depth of scoring is much less here than observed in the large-scale profiles.

The fourth profile (*d – d'* in Fig. 9) was surveyed across a more heavily weathered section where all signs of striations have been erased. The rock face (Fig. 10B) is commonly pitted by chemical weathering, there is some differential erosion with bedding, and many of the smaller "roughness elements" are weathered-out crinoid stems and other fossils.

The profile data can be analyzed for fractal "self-similarity" characteristics by means of Richardson divider analysis (Mandelbrot 1983). In effect, a map divider is walked along the wandering curve of the profile trace, with the spacing of divider points and number of steps giving an estimate of the trace length. Different divider spacings (step lengths) result in different measured lengths of the same trace, with the value of measured length generally increasing as step length is reduced. If the trace shape is a simple fractal (such as Figure 7), then the relationship of measured length to step length gives a sloping, straight-line plot on logarithmic paper, the slope being equal to $1–D$, where D is the estimated fractal dimension of the curve. This log-linear relationship applies within limited ranges of scale (step length) for a number of naturally occurring forms. Within those ranges of scale, small geometrical features, large features, and different features of the same size need not be absolutely identical, but only similar in degree of "roughness."

Richardson analysis was performed digitally on each of the collected profiles. The analysis data plots (Fig. 11) are not simply linear. Instead the plots show linear, sloping segments for step lengths ranging from a few millimeters up to about 10 cm (4 in), at which point the plots diverge to give higher slopes. Striations (D = 1.005) are characterized by quite smooth profiles, and the chemically weathered surface (D = 1.023) is significantly rougher within the same range of scales, but the groove profiles at scales above 10 cm (D = approx. 1.07) are distinctly rougher than either small-scale surface type. The plots (Fig. 11) show this change in form with scale to be abrupt rather than gradual. This analysis method helps us look past the multi-scaled irregularity of the profiles (Fig. 12) to separate out essential differences in geometry.

A difference in geometry of the eroded surface suggests a difference in the processes attacking the surface. The obvious example here is the difference in small-scale geometry between results of glacial tooling and near-surface chemical weathering. The more intriguing case at this site is the difference in process implied for subglacial erosion at scales above and below 10 cm (4 in). This may indicate that entirely different processes have been at work on the two ranges of scale, or possibly that the same process behaves so as to yield quite different results at different scales of action on the same surface, the shift in behavior being distinct rather than continuous.

SOME INTEGRATION OF OBSERVATION AND THEORY. As noted above, the change in geometry of these subglacial erosion features with change in scale also marks a threshold at which controversy begins. The glacial polish and striations are almost universally attributed to abrasion by ice-bound tools (Goldthwait 1979). If there is any surprise here in the

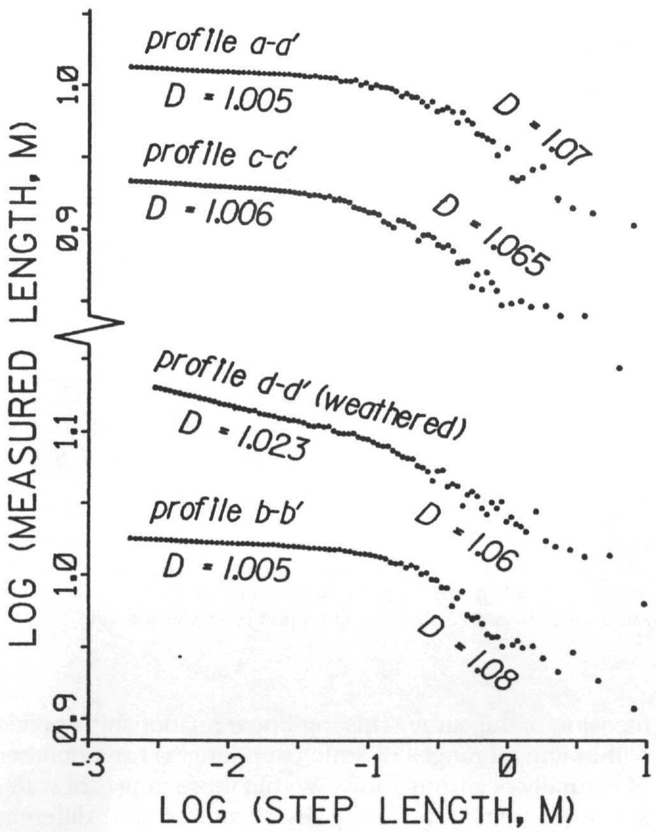

FIGURE 11. Plots resulting from Richardson divider analysis of the profile data sets. Straight, sloping segments of the plots show ranges of scale within which geometric forms are similar. Higher plot slopes indicate higher relative roughness of the surface, quantified by higher values of fractal dimension, *D*. As larger step lengths are used in the analysis (right portions of plots), more data scatter can be expected because of the "small sample size" effect from taking only a few large steps.

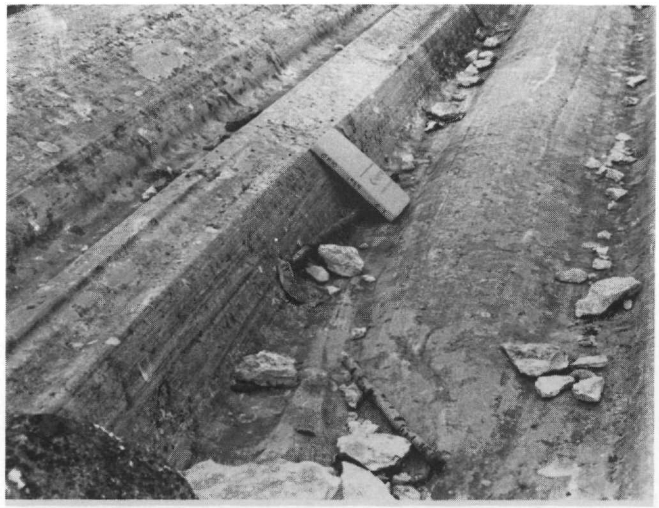

FIGURE 12. Fluting of the surface within the megagroove (Stop 2) showing relative roughness of profile features larger and smaller than the 10 cm (4 in) threshold that has been documented by the fractal analysis. The long axis of the notebook is 20 cm (8 in).

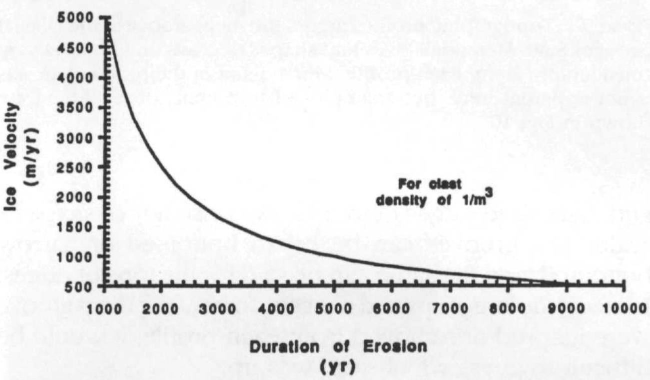

FIGURE 13. Relationship between the ice velocity and duration of erosion necessary to cut a 5 m deep groove by abrasion alone. For this analysis it is assumed that each pass of a clast cuts a 1 mm deep striation.

fractal-analysis results, it is only that scorings up to near 10 cm (4 in) across are in the same geometric set with the striations. On the other hand, the megagroove, the CHRs or sine grooves, and other associated large-scale features have origins that are much less clear.

Several of the hypotheses described above seem at odds with current glaciology and surficial-process theory. For example, let us consider repeated scratching as a process for the cutting of the large grooves. The grooves are about 5 m deep and individual striations here average about 1 mm deep and 2 mm wide (Goldthwait 1979). Thus, to cut to a 5 m depth requires the summation of 5,000 striations, or the passing of 5,000 clasts. If we know the clast density and clast speed, we can assess whether simple abrasion cut the grooves. Goldthwait (1979) found 203 stones in 250 m^3 of till when the grooves were excavated, which translates into about 1 clast/m^3 of till. Not all these clasts would be located at the base, and few of those would pass over any single spot on the bed. A 2 mm wide particle tip would have less than a 1-in-500-chance of being in the correct lateral position on a meter's width of bed (this does not consider the necessity that the clast be oriented correctly). If the clast is 5 cm across, we might conservatively assume a 1-in-20-chance of its being in contact with the bed. Thus, for the 2-mm-wide spot which requires 5,000 clasts to erode it, a minimum of 5 million clasts must move through a meter-wide lateral section before the right 5,000 can do their work.

The 5 million could pass in a short time if the ice velocity were high, or over a long time if the ice velocity were low. Goldthwait (1979) argues the grooves were cut in less than 10,000 yr (probably much less). Assuming a cubic meter of till in each meter width of ice near the bed, this would imply ice velocity of 500 m/yr, or higher (Fig. 13). It can be noted that few modern glaciers exceed 500 m/yr for any length of time. Surging glaciers may move 5 km/yr, but only for a few years. This suggests that most of the megagroove was already present before glaciation, or that other subglacial processes did the work.

Goldthwait (1979) argues that stream action produced the initial loci of the grooves. Ver Steeg and Yunck (1935) describe the nine then-known megagrooves as parallel to each other and located in clusters. Interglacial streams flowing eastward down the Columbus Limestone cuesta might erode small bedrock valleys generally parallel to each other, but it seems odd that those courses should be so independent locally of the joint traces they cross. In addition, the set of stream channels of any particular order will typically be well distributed over a landscape rather than highly clustered, because adequate drainages are necessary to maintain the channels. Stream action does not seem likely as the process responsible for initial cutting of the megagrooves.

What about subglacial meltwater? When fluids carrying sediment abrade the bed over which they are flowing, they usually leave a distinct set of streamlined forms with shapes that reflect a minimum-energy (least work) flow configuration. The form's width-to-length ratio is the usual way to quantify this. For example, Baker (1978) found that most of the streamlined forms in the Channeled Scabland have a ratio of 1:3. Likewise, Greeley and Iversen (1985) found that wind-erosional forms (yardangs) have ratios of 1:3 to 1:10. The theoretical shape for minimum drag is 1:4. On the other hand, the forms observed here and at Marblehead have tails very long relative to head width, with ratios being in many cases less than 1:20 (1:45, for the large ridge at Stop 1). J. Shaw (personal communication) states that long tails of erosional forms are possible in flows with a very high Reynolds number. Baker (1978) found a slight elongation of the forms with increasing Reynolds number, but extrapolation from that data regression would give Reynolds numbers exceeding one billion for many of the forms observed here.

The objective in this section has been to highlight the need for further work in development and evaluation of hypotheses for genesis of these forms. Many questions remain to be discussed.

Questions

- Is there really only one dominant second-order erosional form in the groove? Do the forms or their density change from one end of the groove to the other?
- What spot on Fig. 1 would you pick to explain the features observed? Could ice cut and striate an overhanging lip? Is the origin of the vertical pothole consistent with any of the hypotheses? Have you noted other features you think are important to consider?
- The abundance of striations suggests sharp and plentiful tools. Where do they come from? If they are igneous or metamorphic rocks from the Canadian Shield, they would already be dull; also, Shield rocks are rare in the till (Carney 1910). If they are the local limestone (and thus the same hardness as the bedrock) why are the striations so long? What is the maximum length that an individual striation can be traced?
- The fractal analysis suggests that some difference in processes occurred in the formation of features smaller than 10 cm (transverse direction), compared to those larger. Find examples of features of both scales, and trace them along ice flow direction. Are these forms alike in longitudinal geometry?
- Examine the rocks at heads of the CHRs. Goldthwait (1979) suggests that concentrations of corals are to be found at the heads of the major ridges and may be responsible for their resistance to erosion. Do you agree?
- Another idea for formation of the ridges is that they were areas protected behind large, temporarily lodged obstacles on the glacier bed. Some of the CHRs have furrows well in front of them. Do these features lend any support or refutation to the obstacle idea? Do you see any relationship between the size of the cigar head and the width of the furrow belt in front of it?
- What similarities or differences can you find between this area and the Marblehead Quarry? Is the same set of processes forming these features? If they are different, what controls the change?

Stop 3: Shoreline Erosion at Table Rock

Location. From the Glacial Grooves State Memorial (Stop 2), proceed south on Division Street to the intersection with Ward Road (at Estes School). Follow Ward Road to the east until it becomes Hamilton Road and intersects with Monagan Road (Fig. 4). Follow Monagan Road north 1.1 km (0.7 mi) to a widened parking spot. The road continues beyond this point, so be sure not to block the way for local vehicles. Proceed cautiously along worn paths to the western shore and Table Rock. Permission not required.

Shoreline Erosion Features. East-facing slopes of the Kelleys Island resistant knob were worn down by the westward-flowing, overriding glacier, producing relatively gentle shore topography of rock platforms and shingle beaches, but western shores stand as cliffs modified mainly by wave attack (Ver Steeg and Yunck 1935). One of the best examples of cliff erosion is found here, on the island's northeast peninsula. In many places, the wave-cut notch extends more than a meter (3 ft) back under the low cliff's lip. Some combination of weathering and wave attack has been very effective along joints, creating sluices that extend well in from the cliff front. Following the tortuous cliff front to the northeast reveals a shoreline of collapsed blocks.

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